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Pressure Effects and Surface Cracks in a Rubbery Particulate Composite

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1 Introduction

During the manufacture, handling, and storage of rubbery particulate composites, cracks develop in the material that threaten structural integrity. Previous fracture tests used edge cracked geometries to simplify analysis. Hopefully, these simple experimental results are applicable to a wide range of crack geometries. However, we can increase our confidence in these testing methods by also testing more realistic crack geometries. In this work, surface cracked specimen experiments supplement previous tests conducted under pressure on single edge notched tension (SENT) specimens[1]. The testing of these specimens under pressure is an attempt to understand the effects of pressure, and to quantify these effects. The use of dual specimen geometries is focused on ensuring that the SENT specimen data represents a fracture toughness that is geometry independent and that the SENT derived fracture parameters can be used in the analysis of semielliptical surface flaws in the structural application.

During use, the rubbery particulate composite experiences rapid pressurization, and the pressure affects the fracture behavior by suppressing the nucleation, growth, and coalescence of voids around the particles in the matrix material. The pressure affects both the point at which a crack begins to grow and the subsequent growth rate. If we apply ambient pressure fracture toughness results to structures experiencing pressure, overly conservative predictions result. A more accurate knowledge of the fracture behavior under pressure will result in substantial cost savings.

Pressure effects have been studied and reported in previous work[1]. These studies examined the effect of pressure on the initiation of crack growth in rubbery particulate composites using single edge notched tension specimens; comparison with initiation toughness results for surface cracked specimens showed good agreement. This work builds upon the previous work by examining the growth rates for both specimen geometries under pressure, and comparing them with the analogous ambient pressure results.

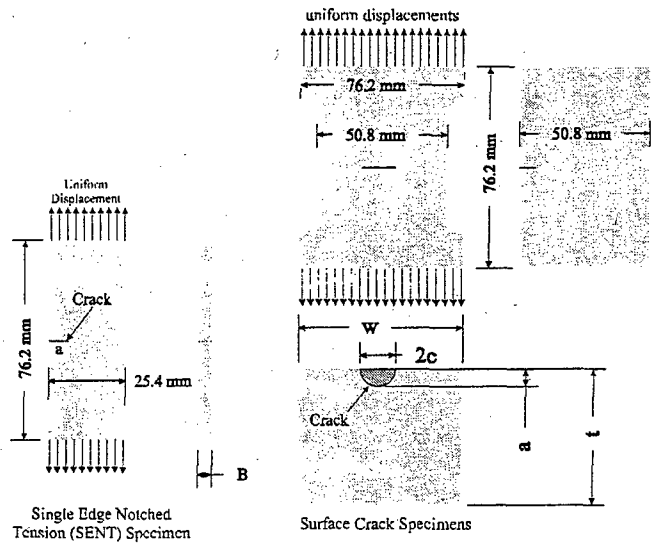

Figure 1: Specimens Used for Fracture Testing Under Pressure

2 Experimental Procedure

The specimens are shown in Figure 1. The SENT specimens and the surface cracked specimens have similar crack sizes. Originally we cut the surface cracked specimens from rectangular blocks, but later we machined them so their net cross sections were reduced because the specimens were glued to the grips with epoxy and had a tendency to debond at the grips.

The SENT specimens had three thicknesses and three crack sizes, as shown in Table 1. The surface cracked specimens we tested had a crack geometry that was approximately semicircular. We created these cracks using a semicircular cutting blade machined from a single edge razor blade. The imposed pressure was 1000 psi and used nitrogen gas.

The equipment consisted of a screw-driven displacement controlled material testing machine, a video camera, a time code generator, and VHS recording equipment. The unique aspect of the setup was a test chamber that

Table 1: Test Matrix for Pressurized Fracture Specimens

		a_0 [mm]		
	B [mm]	2.54	7.62	12.70
Number of SENT specimens tested	5.08	3	3	3
	12.70	3	3	3
	38.10	3	3	3
Number of Surface Cracked Specimens		6		

resided in-line with the testing machine, and applies pressure to the specimens throughout the test. The cracked specimen is mounted in the chamber and pressure is applied and held until the pressure and temperature have stabilized. After this, the specimen is pulled at a constant crosshead speed and is videotaped through sight ports. The videotape equipment records the initiation of growth, the subsequent growth, and the final fracture.

Data analysis involved using the videotape clips and testing machine data to produce predictions of crack growth initiation and a comparison of the subsequent growth rates. The two time scales must be synchronized, since it is difficult to start the video equipment at the exact time that the testing machine begins recording data. We converted the loads to stress intensity factors using linear elastic fracture mechanics principles. The crack sizes are used to determine the crack speeds, and the variables da/dt and K are then related.

During the initial analysis of the videotape, the time at which the cracks begin to grow must be found. This comes from visual observations of the specimen surface from videotape. After growth initiation, the crack sizes are measured periodically. For the SENT specimens, the crack size a was measured. The surface crack measurements consisted of measuring the total crack width $2c$. These cracks began almost semicircular, and were assumed to grow in a self-similar fashion (previous work on similar composite systems shows that this assumption was reasonable). Because of the pressure chamber constraints, we could not measure the crack depth directly.

After measurement of the crack size vs. time, the crack speed can be determined, although this is more complicated than it first appears. The reason is that the microstructure of the rubbery particulate composite consists of a large volume fraction of hard particles embedded in a rubbery matrix. During deformation of a fracture specimen, stresses and strains are largest near the tip of the crack, so the crack tip focuses damage near it. In this material system, damage consists of de-wetting of the hard particles from the matrix material and void growth from the de-wetted particles[2,3].

During deformation, the damage accumulates near the tip of the crack, and a large amount of crack tip blunting takes place. Once the damage reaches some critical level, the crack tip moves forward, and then crack growth slows while damage is reestablished. This results in a sporadic instantaneous growth rate that does not correlate well with loads or any fracture parameter. However, when the data is smoothed, the smoothed crack speed increases with stress intensity. Because the time-averaged crack speed (rather than the instantaneous crack speed) is the relevant variable in this study, we used polynomial curve fitting techniques[4]. Quadratic polynomials were fit to the crack size vs. time data, and the derivatives of these polynomials then provided the crack speed. This procedure gives smoothed data that gives crack speed values that increase with increasing K.

To describe the relationship between crack speed and K, the values for K at different times must be determined. The values for K depend on crack size and load. The K values are calculated using the familiar concept of a geometric correction factor:

$$K = \sigma\sqrt{\pi a} f(\text{geometry}) \tag{1}$$

Here σ is the nominal stress, a is a crack size, and f is a geometric correction factor. For the SENT specimens, we accounted for the geometry using a correction factor that depended only on the ratio of crack size to width, a/w. This was determined using finite element analysis of the SENT specimen geometry. For the surface cracked specimens, the correction factor depended on a/t and c/w (see Figure 1), and accounts for finite specimen thickness and width. Since we assumed the crack maintained a semicircular crack front, the aspect ratio a/c was considered constant and was not incorporated into the geometric correction factor. Newman and Raju[5] previously determined the geometric correction factor and we simplified it by letting $a = c$.

Having determined the crack growth rates and stress intensity factors, we now plotted the data on a log-log scale. The inherent assumption is that the data fits a power law description[4]:

$$\frac{da}{dt} = CK^m \tag{2}$$

Here C and m are parameters that depend on the material system considered but may also depend on other

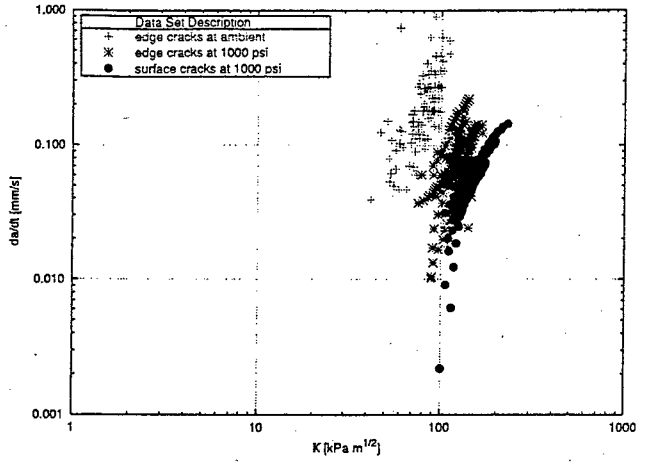

Figure 2: Specimens Used for Fracture Testing Under Pressure

factors (in this case pressure).

3 Results and Discussion

Figure 2 shows the results. This is a log-log plot of da/dt vs. K, and shows previous results for SENT specimens tested at ambient pressure. As the figure shows, the ambient pressure cracks grow at a much higher rate than either of the datasets tested under pressure. This confirms previous research results and is explained by the tendency of the external pressure to suppress the void growth and coalescence processes that occur near the crack tip and cause crack growth. Hydrostatic tension highly favors the growth of voids, and the external pressure superposes a hydrostatic pressure component onto the existing near-tip hydrostatic tension, causing a reduced overall dilatational stress near the crack tip and slowing the process of void growth and coalescence. A comparison of the SENT specimen data under pressure with the surface cracked specimens show that similar crack growth rates are experienced. This indicates that we can use the SENT specimens to predict crack growth rates in surface cracked specimens, and vice versa.

A related issue is the stress intensity factor at the initiation of crack growth. The microstructural phenomena of void nucleation, growth, and coalescence also affect the initiation of crack growth, and suppress the onset of crack growth. The previous research efforts analyzed the stress intensity factors at initiation, and the table below summarizes the results. Again, good agreement is found for the SENT and surface cracked specimens under pressure, and the suppression of fracture events is again evident by comparison of the ambient and pressurized data The fracture toughness at initiation of growth

Table 2: Stress Factors at Initiation of Crack Growth

Condition	K_{Ii} [kPa $\sqrt{m}$]
SENT specimens at ambient pressure	57.0
SENT specimens at 1000 psi	115.6
surface cracked specimens at 1000 psi	108.0

is about doubled by applying 1000 psi pressure.

The results show that pressure inhibits the initiation of growth of cracks and slows the subsequent growth of these cracks in a rubbery particulate composite. The exact amount of retardation must be determined by experiment and is valid only at or near the anticipated service pressure. The data clearly shows that ambient pressure data to be overconservative, and the additional work needed to conduct pressurized tests is warranted by the extent of the differences and by the cost savings attainable by more accurate predictions.

4 Summary and Conclusions

This work has investigated the effect of pressure on fracture behavior of a rubbery particulate composite, and the possible correlation of results between SENT and surface cracked specimen geometries. The pressure affects fracture by inhibiting the start of crack growth, and it slows the subsequent crack growth. These effects were significant and make testing under pressure conditions desirable. The results under pressure for the two specimen geometries were in good agreement, suggesting that we could use the simpler SENT specimens to determine the initiation fracture toughness and the crack growth rates for surface cracked geometries. The conclusions are (i) that pressure inhibits the start of crack growth in a rubbery particulate composite, (ii) that it also slows the growth of the crack after initiation of growth, and (iii) that there is good agreement between the SENT and surface cracked specimens tested under pressure.

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